ADVANCED NUCLEAR SYSTEM FOR THE 21ST CENTURY*

by

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As we start the 21st century in a new millennium, the pressure of energy demand growth is expected to be an acute problem around the world. To meet the energy challenge, we have to exploit all energy options, including renewable sources. But their contribution is inherently limited in magnitude. Fossil energy sources--coal, oil and natural gas--are most readily available, but they raise concerns on global climate change. Nuclear energy today contributes almost 20% of the electrical energy. Over the past decade, nuclear plants have improved their operational reliability, safety records, and economic competitiveness, and nuclear energy is now recognized as an energy technology that can generate large amounts of electricity without producing the greenhouse gases and other environmental pollutants.

Therefore, nuclear is the technology of choice to meet the ever-expanding electrical energy demand. However, nuclear energy faces challenges and some crucial questions require answers before a second nuclear era can contribute significantly toward the energy needs of the 21st century.

There are two issues that must be dealt with promptly: developing a technology solution to the problem of disposition of the nuclear waste that is accumulating at nuclear power plants around the world; and improving the international control of materials that could be used in nuclear explosives. Achieving the longer-term goal for nuclear energy will also require successful resolution of three additional issues: maintaining the high level of nuclear power plant safety as more plants are installed; extending uranium resources so that energy potential is not limited by resource availability; and financing the construction of a new, larger nuclear infrastructure and achieving economic competitiveness with other electricity production options.

There is a growing international consensus that these five criteria are what the next-generation advanced nuclear system must meet to be broadly acceptable for the 21st century and beyond, namely:

X Reduce the volume and toxicity of nuclear waste.
X Keep nuclear materials unsuitable for direct use in weapons.
X Be passively safe based on characteristics inherent in the reactor design and materials.
X Provide a long-term energy source not limited by resources.
X Be economically competitive with other electricity sources.

The only concept we know of that can meet all five requirements is a fast reactor system with a closed fuel cycle based on pyroprocessing. The pyroprocessing developed and demonstrated at Argonne National Laboratory is a key innovation in fuel cycle technology, which promises revolutionary improvements in waste management, nonproliferation characteristics and economics. A simplified pyroprocessing flowsheet is illustrated in Fig. 1.

The key element of pyroprocessing is electrorefining. Spent fuel rods chopped into small pieces are loaded in the anode basket. One type of cathode recovers uranium and the second cathode recovers all other actinide elements together: Pu, Np, Am, Cm, and some uranium. The anode basket that contains cladding hulls and noble metal fission products is melted to a metallic high-level waste form. Electrolyte salts that contain most of the fission products are passed through zeolite columns. Fission products then get immobilized into the zeolite molecular structure through ion exchange and occlusion. The zeolite powder is then mixed with glass frits and melted at high temperature to form a ceramic waste form, called sodalite. Pyroprocessing was originally developed for the fast reactor application, but it could treat spent fuel from today's commercial reactors with the addition of a front-end step to convert the oxide to metal.

The radiological toxicity associated with the spent fuel has two components. As illustrated in Fig. 2, fission products, which have about 30-year half-life, decay in about 300 years below the toxicity level of natural uranium ore. Actinides, on the other hand, have long half-lives and their toxicity level is orders of magnitude greater for millions of years.

In pyroprocessing, the actinides are easily recovered and recycled back into the reactor for fissioning. The effective lifetime of the waste is reduced from millions of years to a few hundred years, at the same time generating energy by burning actinides. This does not obviate the need for a repository, but the technical performance requirements placed on the repository can be met more easily without the long-lived actinides. Furthermore, the repository capacity can be increased substantially because the long-term heat source is eliminated.

Pyroprocessing eliminates the ability to use the reactor's nuclear materials directly in weapons because it cannot separate pure enough Pu. Instead, it keeps the major nuclear fuels, uranium and Pu, mixed at all times with other actinides and fission products. This mixture is protected against theft or unauthorized diversion because the mixture is extremely radioactive and must be handled remotely with sophisticated and specialized equipment. Pyroprocessing involves compact equipment systems and the fuel cycle facility can easily be collocated with the reactor plant, eliminating the need for nuclear fuel transportation.

The waste reduction and nonproliferation benefits of pyroprocessing were recognized by the National Energy Policy, approved by the President in May 2001, which recommended:

> *"in the context of developing advanced nuclear cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium, worldwide."*

> *"The United States should also consider technologies, in collaboration with international partners with highly developed fuel cycles and record of close cooperation, to develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant."*

Today's reactors are perfectly safe, but if we are going to have thousands of reactors around the world, then we should have a higher level of passive safety, that is, safety would be inherent in its design and materials and not solely dependent on engineered safety systems nor operator actions. A fast reactor, especially fueled with metallic fuel, can be designed for such a passive safety, and this was demonstrated in two landmark tests conducted on EBR-II in 1986.

The tests demonstrated that even most severe accidents would not damage the reactor or release radioactive material. In one test, the power was shut off to the pumps that circulate coolant through the core, and in the other, all heat removal was cut off. In both tests, the reactor safely shut itself down without human or mechanical intervention. In any other reactor types, this would cause a severe accident. The passive safety characteristic is uniquely achieved in the metallic-fueled fast reactor because of a combination of three factors: sodium coolant with a very high boiling temperature, pool design configuration providing thermal inertia, and metal fuel with a small Doppler reactivity effect.

The outstanding record of the EBR-II operation over 30 years demonstrated the advantages of a fast reactor system with sodium cooling. Because the sodium boiling temperature is very high, the cooling system can operate at essentially atmospheric pressure. Sodium is also noncorrosive to structural materials used in the reactor. These unique characteristics of a sodium-cooled system result in superior reliability, operability, maintainability and long lifetime, all of which contribute to low life-cycle costs. For example, the EBR-II steam generators had operated over 30 years without a single tube leak, and after draining of the primary sodium, the original "fit-up" chalk markings were still clearly legible on the reactor vessel wall.

Much of the pyroprocessing technology was successfully demonstrated at Argonne-West as part of the three-year (between 1997 and 2000) demonstration project treating 100 EBR-II driver fuel assemblies and 18 blanket assemblies. A special committee of the National Academy of Sciences found that this demonstration project met all criteria for success, and the Department of Energy followed with a formal decision to use this technology to treat the remaining 25 metric tons of EBR-II spent fuel. Going beyond EBR-II spent fuel treatment, a full pyroprocessing demonstration could be accomplished using Argonne-West's existing facilities. This would include recovery of actinides, qualification of waste forms, and enough production capacity to show that it can work on a commercial scale. It would also demonstrate the conversion of commercial oxide fuels to the metallic form and the ability of compact metal and ceramic forms to safely contain short-lived wastes. A logical next step would be a commercial-scale prototype fuel cycle facility that can process 100 metric tons of LWR spent fuel per year.

As for a commercial-scale fast reactor demonstration project, it should be established based on the results of an international collaboration. International collaboration will facilitate incorporation of the lessons learned in fast reactor operating experience around the world, and also development of a consensus on the technology choice. In particular, the U.S. and Japan have a long history of collaboration in the fast reactor base technologies--physics, safety, fuels and materials, sodium components, and advanced design concepts. A continued and enhanced international collaboration will be essential to successful demonstration and deployment of the advanced fast reactor system to meet the challenges of the 21st century.

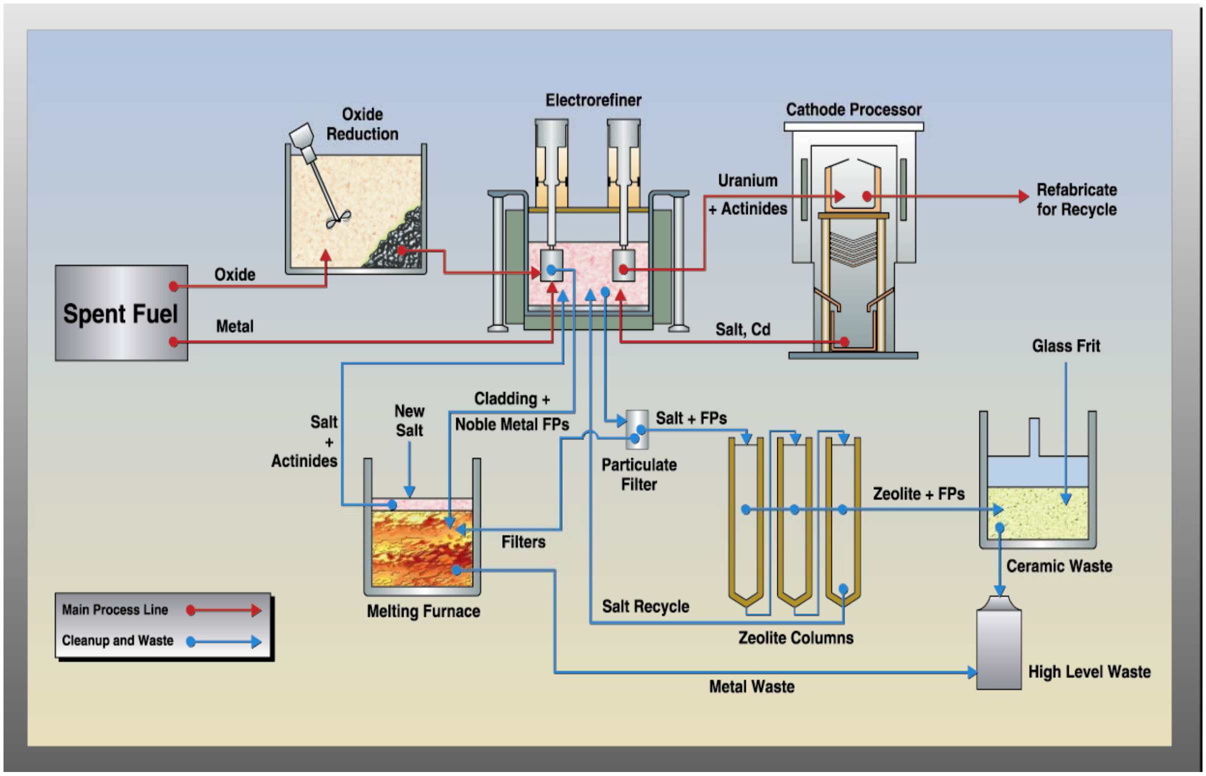
Oxide
Reduction
Electrorefiner
Cathode Processor
Uranium
+ Actinides
Refabricate
for Recycle
Spent Fuel
Oxide
Metal
Salt, Cd
Glass Frit
Salt
+
Actinides
New
Salt
Cladding +
Noble Metal FPs
Salt + FPs
Particulate
Filter
Zeolite + FPs
Filters
Ceramic Waste
Main Process Line
Cleanup and Waste
Melting Furnace
Salt Recycle
Zeolite Columns
High Level Waste
Metal Waste

Figure 1.

SPENT FUEL RADIOLOGICAL TOXICITY

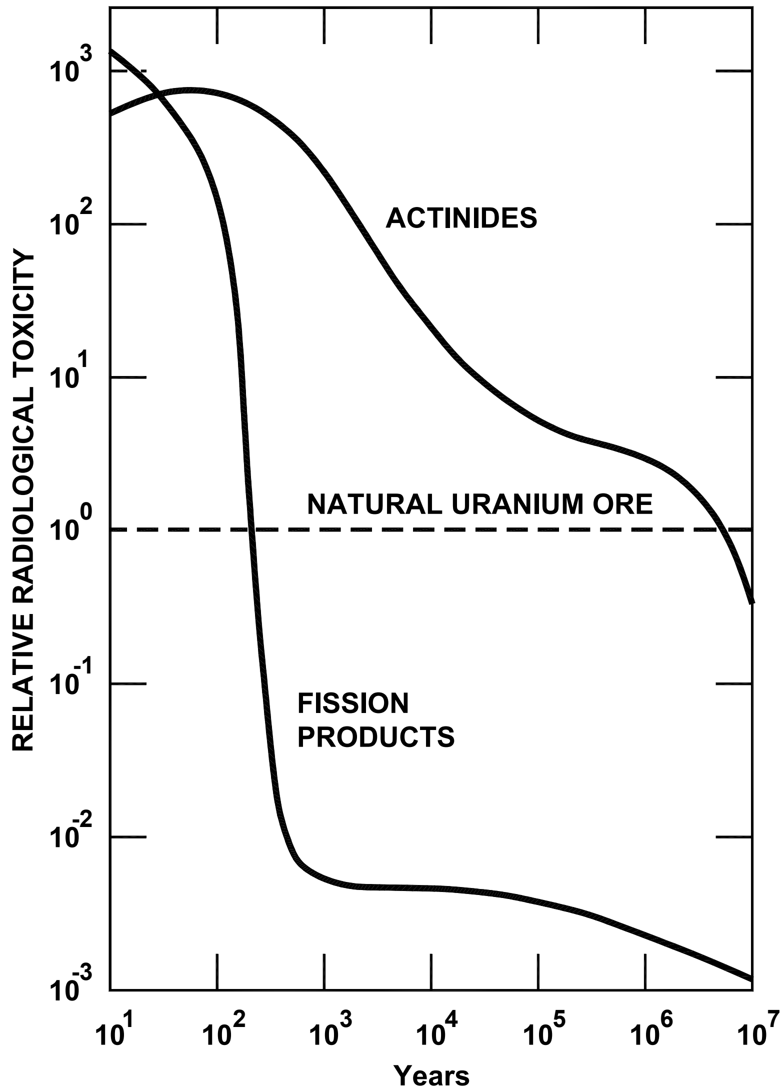

Figure 2.